The half-composite 2HDM and the relaxion

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Outline

- The half-composite 2HDM
- Phenomenology
- Relaxion mechanism
- Conclusions

Vector-like confinement framework

- We take SM with elementary Higgs and add NF new "hyperquarks" Ψ charged under new "hypercolor" interactions

- We also assume that hyperquarks lie in a real representation under the SM so that their condensate does not break EW

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \bar{\Psi}_i (i\not{D} - m_i)\Psi_i - \frac{\mathcal{G}^{A2}_{\mu\nu}}{4g^2_{\rm TC}} + \frac{\theta_{\rm TC}}{32\pi^2}\mathcal{G}^A_{\mu\nu}\tilde{\mathcal{G}}^A_{\mu\nu} + [H\bar{\Psi}_i(y^L_{ij}P_L + y^R_{ij}P_R)\Psi_j + \text{h.c.}]$$

$$\supset |D_\mu H|^2 - \lambda(H^\dagger H)^2 + m^2 H^\dagger H$$

Why bother?

- Natural DM candidates (hyperbaryons and hyperpions) to be probed in the next round of DM experiments
- Each model predicts concrete set of hypermesons to be probed at LHC 13
- Deviations in the Higgs couplings and EDMs
- Automatic MFV to avoid all flavor bounds
- Naturalness is solved via relaxion mechanism (or by hypothesis of scale invariance)

Case study : "L+N" model (NF=3)

Add lepton doublet L and singlet N in the fundamental of new QCD'

$$\mathcal{L}_M = m_L L L^c + m_N N N^c + y H L N^c + \tilde{y} H^\dagger L^c N + h.c.$$

$$\text{CP phase :} \qquad \text{Im}(m_L m_N y^* \tilde{y}^*)$$

After χSB, octet of SU(3) GB decompose under EW as:

$$8 = 3_0 \oplus 2_{\pm 1/2} \oplus 1_0$$

$$\Pi = \begin{pmatrix} \pi_3^0/\sqrt{2} + \eta/\sqrt{6} & \pi_3^+ & K_2^+ \\ \pi_3^- & -\pi_3^0/\sqrt{2} + \eta/\sqrt{6} & K_2^0 \\ K_2^- & \bar{K}_2^0 & -2\eta/\sqrt{6} \end{pmatrix} + \frac{\eta'}{\sqrt{3}} \mathbb{1}_3 .$$

Low energy effective theory

Yukawas and explicit masses

$U(1)_A$ anomaly

$$\mathcal{L} = \frac{f_\pi^2}{4}\mathrm{Tr}[D_\mu U D^\mu U^\dagger] + (g_\rho f_\pi^3 Tr[MU] + h.c) + \frac{f_\pi^2}{16}\frac{a}{N}\left[\ln(\det U) - \ln(\det U^\dagger)\right]^2$$
$$- \frac{N}{16\pi^2 f_\pi}\sum_{G_1,G_2} g_{G_1} g_{G_2} Tr[\pi^a T^a F^{(G_1)}\tilde{F}^{(G_2)}] + \frac{3 g_2^2 g_\rho^2 f_\pi^4}{2(4\pi)^2}\sum_{i=1..3}\mathrm{Tr}[U T^i U^\dagger T^i]$$

Anomaly with SM vectors

1-loop gauge contribution

$$M = \begin{pmatrix} m_L & 0 & yh^+ \\ 0 & m_L & yh^0 \\ \tilde{y}h^- & \tilde{y}h^{0\dagger} & m_N \end{pmatrix}$$

and

$$U \equiv e^{i\sqrt{2}\Pi/f_\pi}$$

Low energy effective theory

Expand around the origin of fields space to cubic order:

$$\mathcal{L}_m = g_\rho f_\pi^3 Tr[MU] + h.c + \frac{3 g_2^2 g_\rho^2 f_\pi^4}{2(4\pi)^2} \sum_{i=1..3} \mathrm{Tr}[U T^i U^\dagger T^i]$$

$\approx$ **mass terms** $\mathrm{Re}[4m_L + 2m_N] g_\rho f_\pi^3 + m_{K_2}^2 K_2^\dagger K_2 - \frac{m_{\pi_3}^2}{2} \pi_3^a \pi_3^a - \frac{m_\eta^2}{2} \eta^2$

$+$ **mixing and trilinear** $i\sqrt{2} g_\rho f_\pi^2 B K_2^\dagger H - \frac{g_\rho}{\sqrt{2}} A f_\pi \left(K_2^\dagger \sigma^a \pi_3^a - \frac{\eta K_2^\dagger}{\sqrt{3}} \right) H + h.c.$

$$- \frac{g_\rho (\mathrm{Im}(m_L) - \mathrm{Im}(m_N))\eta}{\sqrt{3}} \left(4 f_\pi^2 - \frac{2\eta^2}{9} \right) - \frac{2 g_\rho \eta}{\sqrt{3}} \left(K_2^\dagger K_2 \mathrm{Im}(m_N) - \frac{1}{2} \pi_3^a \pi_3^a \mathrm{Im}(m_L) \right)$$

$+$ **η-tadpole** $\frac{2}{3} g_\rho (2\mathrm{Im}(m_L) + \mathrm{Im}(m_N)) K_2^\dagger \sigma^a K_2 \pi_3^a$

$$A \equiv (y + \tilde{y}^*) \qquad B \equiv (y - \tilde{y}^*)$$

mass terms+mixing +trilinear

$$m_{K_2}^2 K_2^\dagger K_2 - \frac{m_{\pi_3}^2}{2}\pi_3^a\pi_3^a - \frac{m_\eta^2}{2}\eta^2$$

$$+ \quad i\sqrt{2}g_\rho f_\pi^2 B K_2^\dagger H - \frac{g_\rho}{\sqrt{2}} A f_\pi \left(K_2^\dagger \sigma^a \pi_3^a - \frac{\eta K_2^\dagger}{\sqrt{3}} \right) H + h.c.$$

$$\epsilon \equiv i\sqrt{2}B\frac{g_\rho f_\pi^2}{m_{K_2}^2}$$

Composite pions vevs:

$$\langle K_2^0 \rangle = \epsilon \langle h^0 \rangle$$

$$\langle \pi_3^0 \rangle = -\frac{4\mathrm{Im}(y\tilde{y})g_\rho^2 f_\pi^3}{m_{K_2}^2 m_{\pi_3}^2}\langle h^0 \rangle^2$$

$$\langle \eta \rangle = \frac{\langle \pi_3^0 \rangle}{\sqrt{3}}\frac{m_{\pi_3}^2}{m_\eta^2} \ ,$$

$$\langle h^0 \rangle^2 = \frac{m^2 + |\epsilon|^2 m_{K_2}^2}{2\lambda}$$

Phenomenology

Type-I 2HDM :

$$\langle K_2 \rangle = \begin{pmatrix} 0 \\ \frac{v_2 e^{i\rho}}{\sqrt{2}} \end{pmatrix} \quad \langle H \rangle = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix} \quad \langle h^0 \rangle = \frac{v_1}{\sqrt{2}} \qquad \frac{v_2 e^{i\rho}}{\sqrt{2}} \equiv \epsilon \langle h^0 \rangle \qquad \tan\beta = \frac{v_2}{v_1} = |\epsilon$$

Deviations in the Higgs couplings:

$$\frac{\tilde{h}_1 VV}{(hVV)^{SM}} \approx 1 - \frac{|\epsilon|^2 m_h^4}{2(m_h^2 - m_{K_2}^2)^2}$$

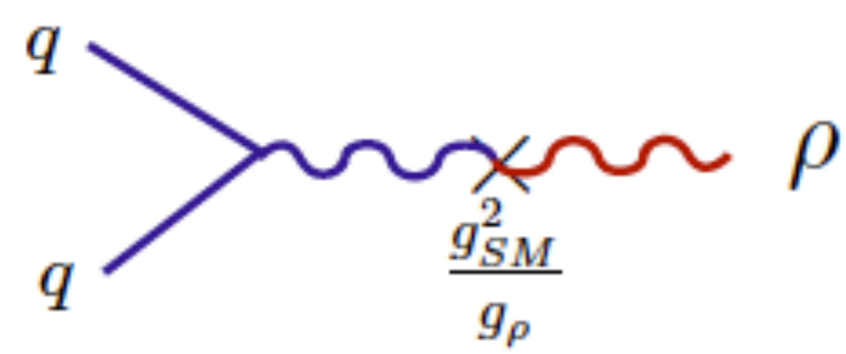
$$\frac{\tilde{h}_1 \bar{f} f}{(h\bar{f}f)^{SM}} \approx 1 - \frac{|\epsilon|^2 (m_{K_2}^2 - 2m_h^2)^2}{2(m_h^2 - m_{K_2}^2)^2}$$

$$\text{EWPT}: \qquad \hat{T} \sim \frac{v^2}{f_\pi^2} |\epsilon|^4 \qquad \hat{S} \sim \frac{m_W^2}{m_\rho^2} |\epsilon|^2 \quad \Longrightarrow \quad \epsilon < 0.03 \times \frac{g_\rho}{g_2} \times \frac{f_\pi}{v}$$

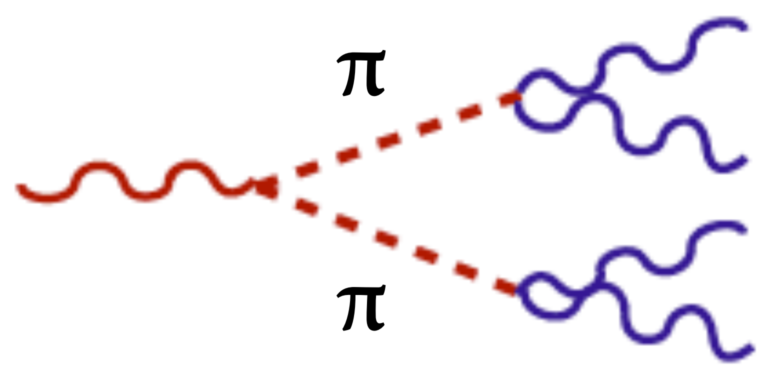
COLLIDER SIGNATURES

Kilic, Okui, Sundrum '09

Vector resonances with SM quantum numbers predicted



Decay to hidden pions and back to SM gauge bosons,



Pions can also be stable or long lived.

Collider phenomenology

From SM anomaly:

$$\frac{N}{16\pi^2 f_\pi} \sum_{G_1,G_2} g_{G_1} g_{G_2} Tr[\pi^a T^a F^{(G_1)} \tilde{F}^{(G_2)}]$$

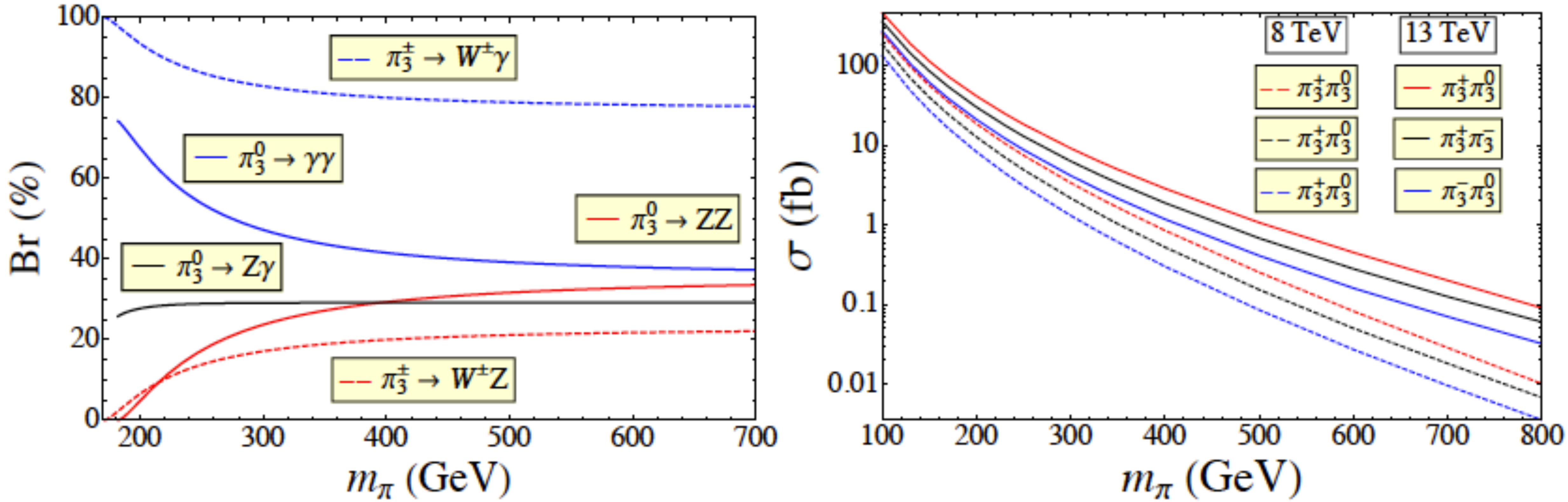


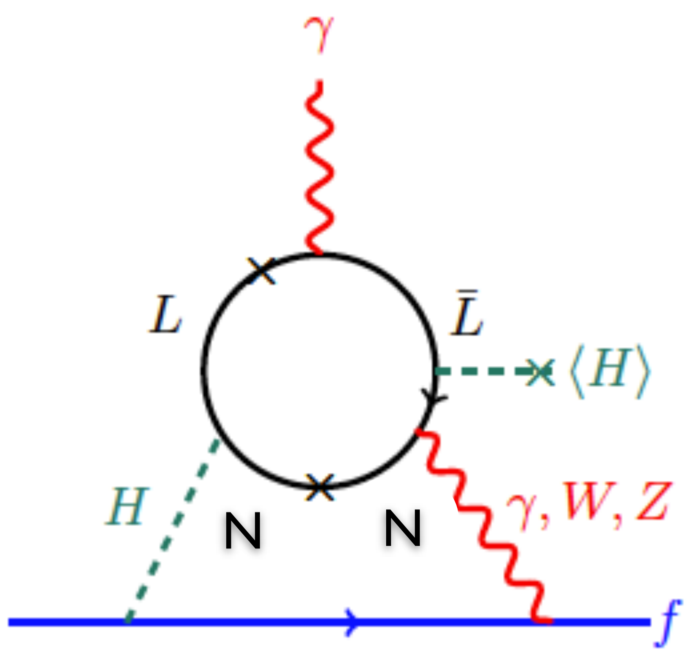
Figure 1: a) On the left, branching fractions of the neutral (solid) and charged (dashed) pion triplets $\pi_3^{0,\pm}$ in $\gamma\gamma$, ZZ, $Z\gamma$, $W^\pm\gamma$ and $W^\pm Z$. b) On the right, partonic production cross-section of scalar triplets at 8 TeV and 13 TeV.

$$m_{\pi_3} > 230 \text{ GeV}$$

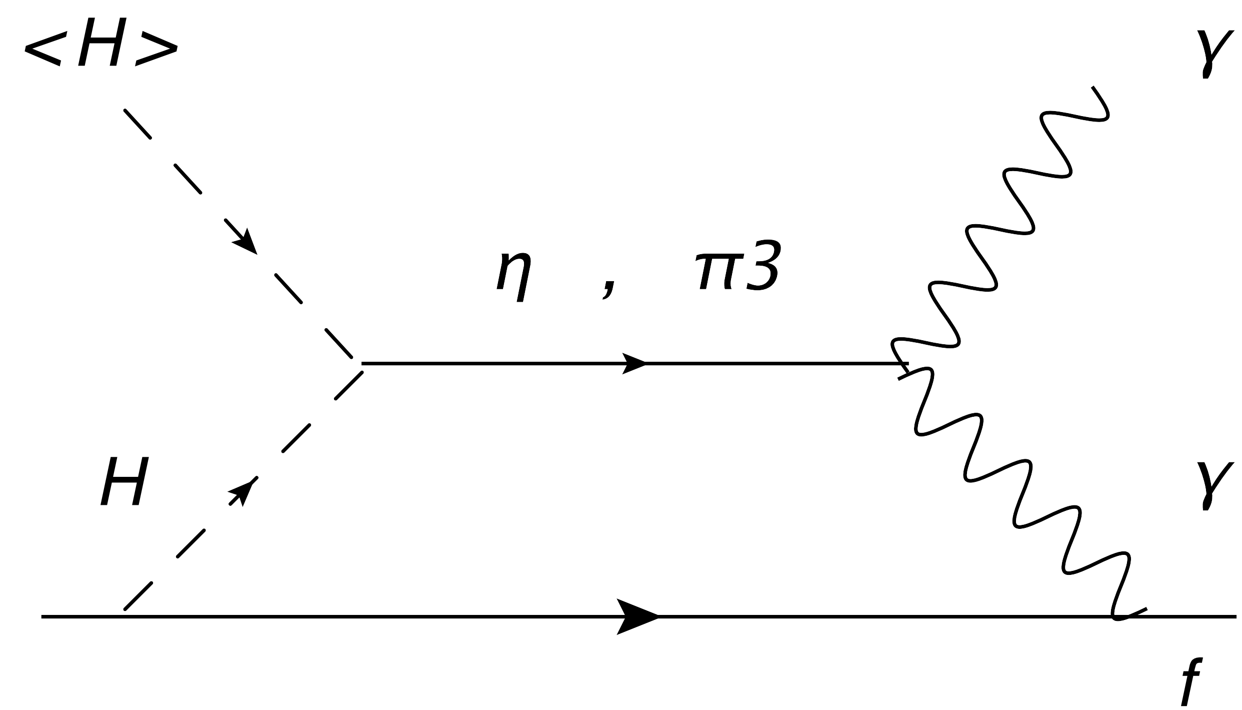
Electron EDM

CP phase : $\mathrm{Im}(m_L m_N y^* \tilde{y}^*)$

Heavy fermions



Light fermions



Integrating out η, π3 : $$L^{\mathrm{eff}}_{\mathrm{EDM}} \supset -\frac{e^2 N}{48\pi^2}\frac{\mathrm{Im}(y\tilde{y})(3m_\eta^2 - 2m_{\pi_3}^2)m_\rho^2}{m_{\pi_3}^2 m_\eta^2 m_{K_2}^2} F\tilde{F}h^{0\dagger}h^0$$

$$d_e \approx 10^{-27}\,\mathrm{e\,cm} \times \mathrm{Im}[y\tilde{y}] \times \frac{N}{3} \times \left(\frac{\mathrm{TeV}}{m_{\pi_3,\eta}}\right)^4 \times \left(\frac{m_\rho}{\mathrm{TeV}}\right)^2$$

What about naturalness?

Relaxion mechanism

arxiv 1504.07551

Minimal model: SM + QCD axion + inflaton

$$V = (-M^2 + g\phi)|h|^2 + gM^2\phi + \frac{\phi}{f}\tilde{G}'_{\mu\nu}G'^{\mu\nu}$$

- Soft-breaking of shift symmetry (via coupling to Higgs)
- Large (non-compact) axion field excursions

How it works?

- During inflation axion slow-rolls and scans Higgs mass
- Once mass gets negative, Higgs obtains a vev
- Axion potential barriers (linear in the vev) grow and stop scanning

$$m_\pi^2 \sim m_q f_\pi \sim y_q < h > f_\pi \quad \Rightarrow \quad y_q f_\pi^3 < h > \cos\frac{\phi}{f}$$

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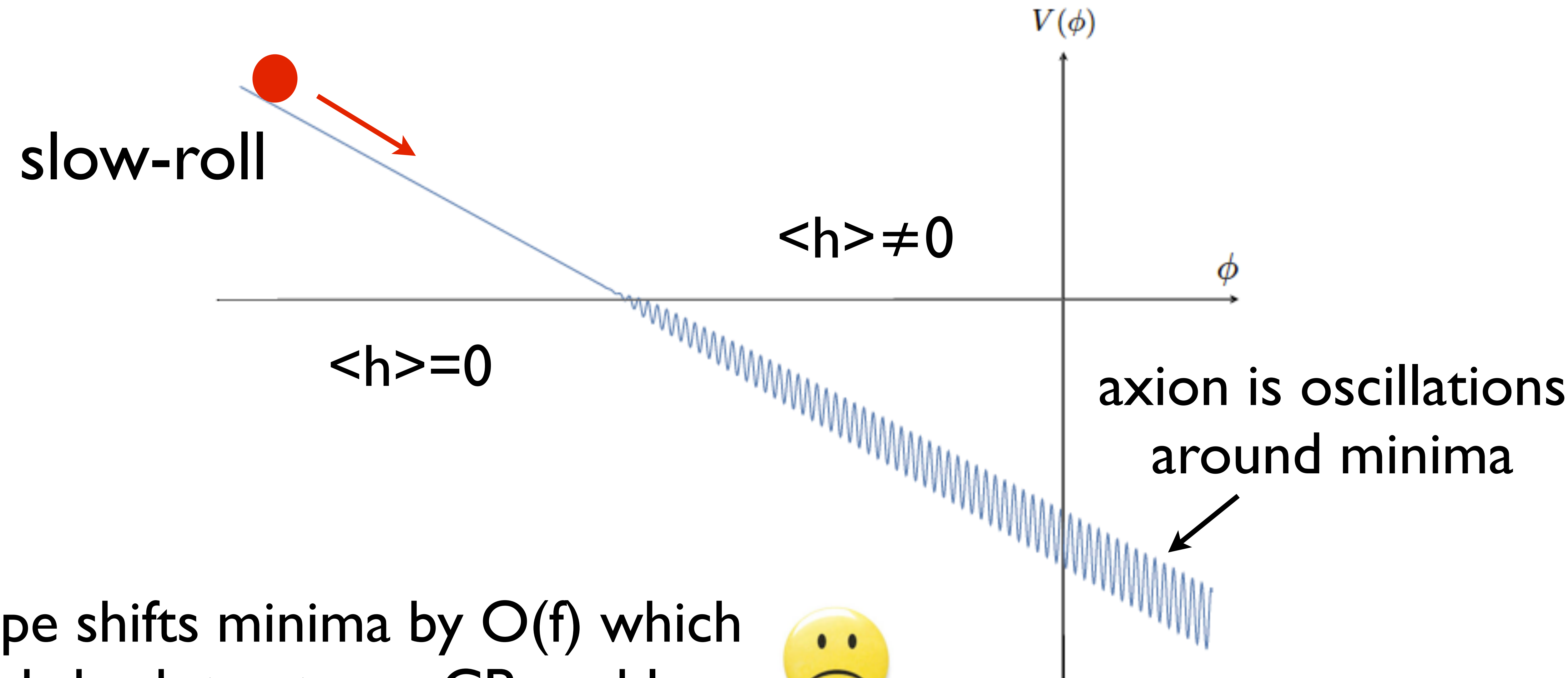
Relaxion mechanism

Rolling stops when slopes match :

$$gM^2 \sim \frac{m_\pi^2 f_\pi^2}{f}$$



Slope shifts minima by O(f) which leads back to strong CP problem

Solution : barriers for axion arise from a new strong group (QCD')

$$\frac{\phi}{f}\tilde{G'}_{\mu\nu}G'^{\mu\nu}$$

and this is precisely our framework

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Compute $E_{\rm vac}(\theta_{TC})$ and replace $\theta_{TC} \to \frac{\phi}{f}$

$$m_N \ll m_L: \quad E(\theta_{TC}) \approx -2m_N g_\rho f^3_\pi \cos\theta_{TC} + 2\frac{g^2_\rho f^4_\pi}{m^2_{K_2}}\left[|y|^2 + |\tilde{y}|^2 - 2|y\tilde{y}|\cos\left(\theta_{TC} - \theta_0\right)\right]|H|^2$$

$$m_L \ll m_N: \quad E(\theta_{TC}) \approx -4m_L g_\rho f^3_\pi \cos\frac{\theta_{TC}}{2} + 2\frac{g^2_\rho f^4_\pi}{m^2_{K_2}}\left[|y|^2 + |\tilde{y}|^2 - 2|y\tilde{y}|\cos\left(\frac{\theta_{TC}}{2} - \theta_0\right)\right]|H|^2$$

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QCD axion barriers : $y_q f_\pi^3 < h >$

Now, barriers : $|y\tilde{y}|\frac{g_\rho^2 f_\pi^4}{m_{K_2}^2} < h >^2$

Scales to be tested at the LHC 13 :

$$m_{K_2} \sim f_\pi \sim \ 500 \text{ GeV and } m_\rho \sim 5 \text{ TeV}$$

Conclusions

- Vector-like confinement is a viable framework to be tested by the next round of experiments
- Within the context of half-composite 2HDM we showed that it leads to interesting collider signatures and electron EDM
- Relaxion mechanism can make these models natural

Back up

Hyperbaryon DM pheno crucially depends on the HB mass:

$$M_{\rm DM} \approx \begin{cases} 100\,\text{TeV} & \text{if DM is a thermal relic,} \\ 3\,\text{TeV} & \text{if DM is a complex state with a TCb asymmetry} \end{cases}$$

Relic abundance determined by non-relativistic annihilation xsec of HB into hyperpions rescaling the measured QCD pp xsec